

## PTF 12GZK - A RAPIDLY DECLINING, HIGH-VELOCITY TYPE IC RADIO SUPERNOVA

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## ABSTRACT

Only a few cases of type Ic supernovae (SNe) with high-velocity ejecta have been discovered and studied. Here we present our analysis of radio and X-ray observations of a Type Ic SN, PTF 12gzk. The radio emission rapidly declined less than 10 days after explosion, suggesting SN ejecta expanding at high velocity ( $\sim 0.3 c$ ). The radio data also indicate that the density of the circumstellar material (CSM) around the supernova is lower by a factor of  $\sim 10$  than the CSM around normal Type Ic SNe. Our observations of this rapidly declining radio SN at a distance of 58 Mpc demonstrates the potential to detect many additional radio SNe, given the new capabilities of the VLA (improved sensitivity and dynamic scheduling), that are currently missed, leading to a biased view of radio SNe Ic. Early optical discovery followed by rapid radio observations would provide a full description of the ejecta velocity distribution and CSM densities around stripped massive star explosions, as well as strong clues about the nature of their progenitor stars.

## 1. INTRODUCTION

There are two diagnostics provided by radio emission from supernovae. First, radio (and X-ray) emission is generated as fast-moving ejecta collide with the circumstellar medium (CSM; Chevalier 1982; Chevalier 1998; Weiler et al. 2002; Chevalier & Fransson 2006). Thus radio and X-ray observations can be used to measure the density of optically thin CSM. Next, radio and X-ray emission can be used to trace the *fastest* moving ejecta. In contrast, the optical emission is reflective of the bulk of the ejecta, where the optical depth to visible-light photons is determined, which is necessarily of lower velocity. From measuring the run of the density one can infer the ratio of the mass loss rate to the escape velocity (wind velocity) of the progenitor star – the mass loading parameter. Radio observations are in good accord with the picture that Type Ib/Ic supernovae arise from stripped massive star progenitors.

Both these diagnostics came to the fore for supernovae associated with Gamma Ray Bursts (GRBs). The first example was SN 1998bw (a broad-lined Type Ic; Ic-BL), associated with the nearby, low-luminosity gamma-ray burst GRB 980425 (Galama et al. 1998). Radio observations established that the fastest moving ejecta were mildly relativistic *and* carried a significant amount of the explosion energy (Kulkarni et al. 1998). The

same approach showed that SN 2009bb (Type Ic-BL) also had mildly relativistic ejecta and it has been reasonably argued that either SN 2009bb did not produce gamma-rays or that the associated GRB was likely not pointed towards us (or we missed detecting the gamma-rays; Soderberg et al. 2010). It is worth noting that in both cases the optical line features were very broad, i.e.,  $0.1 c$ . This discussion naturally raises the issue whether there exists supernovae which are intermediate (in the above two senses) between ordinary Ib/Ic supernovae and SN 1998bw and SN 2009bb.

Here, we report on radio observations of PTF 12gzk, a Type Ic supernova which showed high-velocity optical features and a luminous optical emission (indicative of large radioactive  $^{56}\text{Ni}$  yield), but without detection of gamma-ray emission. PTF 12gzk turned out to be a fast-evolving radio SN, but with a lower shockwave velocity (inferred from the radio emission) and energy than SN 2009bb. At the same time, the velocities inferred from the optical spectra resemble those of SN 1998bw and SN 2009bb. This raises the possibility that PTF 12gzk is an intermediate object, connecting normal SNe Ic with GRB-SNe (as discussed above).

In §2 we describe our observation and analyze them in §3. We then discuss the nature of PTF 12gzk in §4. We summarize our results and discuss their implications on future studies in §5.

## 2. MULTI-WAVELENGTH OBSERVATIONS

2.1. *The Optical Discovery of PTF 12gzk*

The Palomar Transient Factory (PTF; Law et al. 2009; Rau et al. 2009) discovered a peculiar SN Ic, PTF 12gzk (Ben-Ami et al. 2012a), as reported in in Ben-Ami et al. (2012b). In short, PTF 12gzk was discovered on 2012 July 24 UTC in the galaxy SDSS J221241.53+003042.7, 58 Mpc away ( $z = 0.0137$ ). The SN was not detected in previous images taken by PTF on July 19, down to a  $3\sigma$  limiting magnitude of 20.6 mag. The SN was detected at a magnitude of  $m = 20.1$  mag in  $r$  band and reached a peak magnitude of  $m = 15$  mag ( $M = -19$ )

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on August 7, 2012. Based on the optical rise time Ben-Ami et al. (2012b) estimate the explosion time to be  $t_0 = 2012 \text{ Jul } 24.0 \pm 1 \text{ d}$ . Followup optical data suggest that PTF 12gzk is a peculiar Type Ic supernova, with high expansion velocities, long rise time and a large radioactive  $^{56}\text{Ni}$  mass, pointing towards an energetic explosion. PTF follow-up programs were rapidly triggered (Gal-Yam et al. 2011) including the *Swift* satellite, the Very Large Array (VLA), and the Combined Array for Research in Millimeter-wave Astronomy (CARMA) to observe PTF 12gzk in X-ray, cm-wavelength, and mm-wavelength, respectively. Additional follow-up observations and analysis (including *HST* UV spectroscopy) are presented in Ben-ami et al. 2013 (in preparation).

### 2.2. Radio Observations

We observed PTF 12gzk using VLA<sup>9</sup> on UTC 2012 August 1. The observation was undertaken in C (6 GHz) band using a 2 GHz bandwidth. The VLA configuration at that time was the B configuration. In our observation we used J2215–0335 as a phase calibrator and 3C48 as a flux calibrator. The data were reduced using the AIPS<sup>10</sup> software.

We detect a source with a flux of  $77 \pm 11 \mu\text{Jy}$  at the position  $\alpha = 22^{\text{h}}12^{\text{m}}41.55^{\text{s}}$ ,  $\delta = 00^{\circ}30'43''1$ , consistent with the optical position of the SN within  $0''.5$ . The radio luminosity is thus  $L_{\nu} = 3 \times 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$ . Splitting the data into two sub-band frequencies we measured a flux of  $79 \pm 16 \mu\text{Jy}$  and  $82 \pm 14 \mu\text{Jy}$  at 4.8 GHz and 7.4 GHz, respectively, implying a spectrum with a power-law index of  $\alpha = 0.1 \pm 0.6$ .

Further VLA observations were performed on UT 2012 August 3, using C, Ku (14 GHz), and K (20 GHz) bands and on UT 2012 August 5 using C band. We do not detect the supernova ( $> 3\sigma$ ) in both the second and third epochs in all bands.

On UT 2012 August 03, we also observed PTF 12gzk with CARMA at a frequency of 95 GHz. The observation was performed in E array and 3C446 was used as the phase calibrator. The data were reduced using the MIRIAD software. The SN was not detected with a  $3\sigma$  upper limit of 3.6 mJy. The log of the cm- and mm-wavelength observations can be found in Table 1.

### 2.3. X-ray Observation

PTF 12gzk was observed by the X-Ray Telescope (XRT; Burrows et al. 2005) and the ultraviolet imaging telescope (UVOT; Roming et al. 2005) on the *Swift* satellite. XRT measurements, beginning at 13:39 UT on July 31, detected no source at the location of PTF 12gzk. We estimate a dead-time-corrected limit on the XRT count rate of  $< 2 \times 10^{-3} \text{ ct s}^{-1}$ . Assuming a power-law spectrum with a photon index of 2, this corresponds to a limit on the X-ray flux of  $< 7 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$  ( $L_X < 2.8 \times 10^{40} \text{ erg s}^{-1}$ ).

### 2.4. A Search for High-energy Emission

We have searched the available public archives for GRBs contemporaneous with PTF 12gzk. Using the inferred constraints on the explosion date from early optical observations (see §2.1), we find no reported GRBs

from either the InterPlanetary Network (IPN; Hurley et al. 2010) or the *Fermi*  $\gamma$ -ray Burst Monitor (GBM; Meegan et al. 2009). Unlike the GBM, the IPN provides essentially continuous all-sky coverage, to a limiting fluence (10 keV – 5 MeV) of  $S_{\gamma} \lesssim 2 \times 10^{-6} \text{ erg cm}^{-2}$ , so we shall adopt this value as a limit on any high-energy emission associated with PTF 12gzk.

The lack of gamma-ray emission from PTF 12gzk therefore suggests that an associated GRB (if one exists) had to be an off-axis event.

## 3. SHOCKWAVE PROPERTIES AND ENERGETICS

The sparse data prevents us from performing any detailed modeling of PTF 12gzk. However, we can approximate the lower limit on the shockwave radius, and therefore its velocity, using the formulation of Chevalier (1998; Equation 13). Assuming equipartition, (i.e., the fraction of shockwave energy converted to electron acceleration is equal to the fraction of energy converted to a magnetic field), and adopting the lower limit on the peak flux at 5 GHz  $F_p \geq 77 \mu\text{Jy}$ , yields a lower limit on the shockwave radius of  $R_s \geq 4.8 \times 10^{15} \text{ cm}$ . The shockwave radius can be translated into a lower limit on the shockwave velocity, assuming that the time of the peak is  $t \leq 7 \text{ days}^{11}$ . Thus,  $v_s = R_s/t \geq 80,000 \text{ km s}^{-1}$ . This can also be graphically inferred from the Chevalier luminosity-peak time diagram (Figure 1).

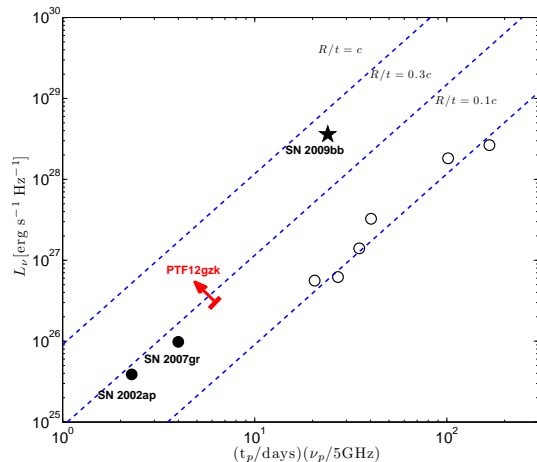


FIG. 1.— Chevalier luminosity-peak time diagram. The open black circles are measurements of “normal” Ic SNe (Chevalier & Fransson 2006 and references therein). The 5-GHz luminosity of PTF 12gzk is  $3 \times 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$  on UT 2012 August 1. Likely this corresponds to a post-explosion epoch of eight days. The radio emission is already decaying. Therefore, the peak time is  $\leq 7$  days. From this we conclude that PTF 12gzk is a high speed Ic supernova with mean ejecta velocity (of the leading edge) in excess of 80,000  $\text{km s}^{-1}$ .

In the same manner, we can approximate the mass-loss rate from the progenitor prior to explosion, using equation 23 from Chevalier & Fransson (2006) and assuming that the CSM around the SN was deposited by

<sup>11</sup> The limit on the time of the peak is estimated based on the explosion time from Ben-ami et al. (2012b) and the assumption that the emission is already fading on UT 2012 August 1. If the emission was still rising on UT 2012 Aug 1, we should have detected the SN on our second epoch of observation less than two days later

<sup>9</sup> VLA program 12A-363 (PI Horesh)

<sup>10</sup> <http://www.aips.nrao.edu>

TABLE 1  
SUMMARY OF RADIO OBSERVATIONS OF PTF 12GZK

Day	Frequency [GHz]	Flux [ $\mu$ Jy]	Observatory
1.42	4.8	$79 \pm 16$	VLA
1.42	7.4	$82 \pm 15$	VLA
3.33	6.1	$\leq 33$	VLA
3.33	14	$\leq 42$	VLA
3.33	20	$\leq 90$	VLA
3.34	95	$\leq 3600$	CARMA
5.55	6.1	$\leq 33$	VLA

Notes - Day is given in UT days in 2012 August. The error in the flux is the rms error measured in each image. Upper limits are  $3\sigma$  limits.

a stellar wind with a constant velocity,  $v_w$ , and a constant mass-loss rate,  $\dot{M}$ . Adopting the value for the fraction of energy of the shockwave that is converted into a magnetic field  $\epsilon_B = 0.1$ , we find that the mass-loading parameter defined as  $A = \frac{\dot{M}}{4\pi v_w}$  is  $A \leq 6 \times 10^{10} \text{ g cm}^{-1}$ . This is also consistent with the upper limit on the X-ray flux, assuming that any X-ray emission originates from inverse-Compton (see Chevalier & Fransson 2006; Soderberg et al. 2012; Horesh et al. 2012).

We note that in our analysis so far we have assumed equipartition ( $\epsilon_e = \epsilon_B$ ). However, as previous studies show, equipartition is not necessarily the case (Soderberg et al. 2012; Horesh et al. 2012). Adopting a more extreme value of  $\epsilon_e/\epsilon_B = 500$  (motivated by the result of Horesh et al. 2012) lowers the lower limit on the shockwave velocity to  $v_s \geq 60,000 \text{ km s}^{-1}$  ( $v_s \propto (\epsilon_e/\epsilon_B)^{-1/19}$ ).

At this point we also would like to note that the change in radio flux between the first and second epochs is significantly larger than would be predicted by a  $t^{-1}$  decay (for a shockwave with a constant velocity and electron energy power-law index of  $p = 3$ ). However, the flux that we measure may be effected by interstellar scattering and scintillation (ISS) and therefore may be intrinsically lower.

Taking into account the ISS modulation index, the intrinsic flux of PTF 12gzk can be as low as  $45 \mu\text{Jy}$ . In this case the shockwave velocity lower limit reduces from  $80,000 \text{ km s}^{-1}$  to  $60,000 \text{ km s}^{-1}$ . Moreover, the difference between the observed reduced flux on the first epoch and the flux limit on the second epoch, is consistent (within the errors) with the expected change in the Chevalier (1998) synchrotron emission model.

We find that the internal minimum energy of the emitting material is  $E_{\min} = 7.3 \times 10^{45} \text{ erg}$  (See equation 7 in Horesh et al. 2012). The energy of an ejecta velocity component in a pure explosion is given by

$$E(v) = E_0 \left( \frac{v}{v_0} \right)^{-5} \quad (1)$$

where  $v_0$  is the maximum velocity of the ejecta and  $E_0$  is the energy carried by it. Considering a radiative progenitor star (polytropic index of  $n = 3$ ), i.e., a Wolf-Rayet (WR) or a blue supergiant (BSG) star, and substituting

the equations of Matzner & McKee (1999)<sup>12</sup> for  $v_0$  and  $E_0$  (see also Nakar & Sari 2010 for the normalizations that are used here) into the above equation, the energy<sup>13</sup> can be now expressed as

$$E_{ej}(v) = 2.3 \times 10^{52} \left( \frac{M}{M_\odot} \right)^{-2.46} \left( \frac{E}{10^{51} \text{ erg}} \right)^{3.48} \times \left( \frac{v}{10,000 \text{ km s}^{-1}} \right)^{-5} \quad (2)$$

Plugging our velocity lower limit,  $v_0 \geq 80,000 \text{ km s}^{-1}$ , into the above equation and adopting the ejecta mass and explosion energy values from Ben-Ami et al. (2012b) ( $M_{ej} = 7.5 M_\odot$  and  $E = 7 \times 10^{51} \text{ erg}$ ) yields  $E_{ej} \approx 4.3 \times 10^{48} \text{ erg}$ . Therefore, there is more than enough energy in the ejecta to account for the shockwave minimum energy that we measure.

#### 4. COMPARISON WITH A SAMPLE OF RADIO-DETECTED SNE IB/C

The two most comparable SNe Ic that also exhibit high shockwave velocities, but are not relativistic, are SN 2002ap (Berger et al. 2002) and SN 2007gr (Soderberg et al. 2010). Both of these sources are believed to be ordinary core-collapse explosions (cf., Paragi et al. 2010). Both SNe had radio emission that evolved relatively fast, with SN 2002ap peaking at  $t \sim 2 - 3$  days (4.86 GHz) and SN 2007gr peaking at  $t \sim 3 - 4$  days (8.46 GHz), after explosion. The radio analysis by both Berger et al. (2002) and Soderberg et al. (2010) suggest shockwave velocities of  $\approx 0.2 - 0.3c$ . For PTF 12gzk, as seen in Figure 1, the lower limit is about  $0.3c$ , similar to the velocities of SN 2002ap and SN 2007gr. However, the two latter SNe had fainter radio luminosities by factors of  $\sim 10$  and  $\sim 3$  compared with PTF 12gzk, respectively. The brighter radio emission from PTF 12gzk may suggest that the shockwave velocity is even higher in this case.

The optical spectra of SN 2002ap, SN 2007gr and PTF 12gzk show significant difference. The spectra of SN 2002ap (Type Ic-BL) exhibit broad lines formed by

<sup>12</sup> Equations 32 & 37 in Matzner & McKee (1999)

<sup>13</sup> This is the energy of the fast-moving ejecta originating from the outer layer of the progenitor star, in contrast to the energy carried by the bulk ejecta that originates from the inner parts of the star.

emission from ejecta with a broad range of velocities. The velocity of the line centers suggests a bulk velocity of  $\sim 38,000 \text{ km s}^{-1}$  7 days prior to optical peak (B-band) that decreased to  $15,000 \text{ km s}^{-1}$  at peak (Gal-Yam, Ofek & Shemmer 2002). In the case of SN 2007gr (normal Ic), there are no broad lines and the absorption line blueshifts suggest a velocity of less than  $13,000 \text{ km s}^{-1}$  (Hunter et al. 2009). PTF 12gzk, in contrast, does not show broad lines<sup>14</sup> as does SN 2002ap, but based on line blueshifts, it does exhibit high expansion velocities of  $\sim 35,000 \text{ km s}^{-1}$ , a factor of  $\sim 3$  higher than the velocity of SN 2007gr. This higher velocity is consistent with our inference that the shock velocity traced by the radio observations is larger than  $0.2 - 0.3c$ .

Another property that PTF 12gzk has in common with SN 2002ap and SN 2007gr is the inferred mass-loading parameter of the SN progenitor. In Table 2 we list the normalized mass-loading parameter,  $A_*$ , values of these three SNe and a few other Ib/c SNe, where  $A_* = A/5 \times 10^{11} \text{ g cm}^{-1}$ . PTF 12gzk, SN 2002ap and SN 2007gr all have  $A_*$  values which are at least a factor of 10 lower than the values for the rest of the listed SNe. This is an interesting clue worthy of further investigation, that may suggest more compact progenitors for these objects, driving faster winds.

## 5. SUMMARY AND FUTURE IMPLICATIONS

We observed PTF 12gzk in mm-, cm-wavelength and X-rays, starting eight days after explosion. Our radio observations reveal a rapidly declining emission that can be explained by a very fast  $\geq 80,000 \text{ km s}^{-1}$  shockwave ploughing through an optically thin CSM, that was deposited by a stellar wind, prior to the explosion. We also calculate the limit on the mass-loading parameter  $A \leq 6 \times 10^{10} \text{ g cm}^{-1}$ , which is consistent with our X-ray observations. Observations of PTF 12gzk can be explained by an ordinary pure explosion supernova, and do not require an engine-driven event. However, its inferred high-velocity shockwave (based on our radio analysis) together with the high velocity of the bulk of the ejecta (based on the optical spectra; Ben-Ami et al. 2012), may indicate that it is an intermediate event between a “normal” SN Ic and a GRB-SN like event.

The fraction of rapidly declining (peak emission at 5 GHz in less than 10 days) radio SNe Ic is not well constrained. While the discovery rate of SNe Ic by PTF is  $\sim 25$  per year on average, many of these past events were discovered many days after explosion. Recently, PTF has adopted a higher survey cadence that enables the discovery of SNe within one day of explosion. Figure 1 in Soderberg et al. (2010) reveals that most of the radio observations of SNe Ic took place at late times. Therefore, most rapidly declining events like PTF 12gzk would have been missed by current observing strategies. Thus, it is possible that the average shockwave velocities of  $0.1 - 0.15c$  observed in normal SNe Ic may not represent the average velocity of the general SN Ic population.

The more improved sensitivity of the VLA offers the opportunity to detect radio emission from high-velocity SNe Ic out to larger distances. Past studies probed

only nearby ( $\leq 10 \text{ Mpc}$ ) rapidly evolving SNe Ic such as SN 2007gr and SN 2002ap, due to limited sensitivity. Given an rms of  $10 \mu\text{Jy}$  in C band, the detection horizon for SNe Ic with a shockwave velocity of  $0.3c$  and with an  $A_*$  value similar to that of PTF 12gzk, is 70 Mpc, and 20 Mpc even for SNe with an  $A_*$  value lower by a factor of 10 than the one of PTF 12gzk. Relativistic events, such as SN 2009bb, will be detectable out to a distance of 100 – 300 Mpc, if they will have an  $A_*$  value similar to that of PTF 12gzk or even lower.

Another possible strategy to better study rapidly evolving radio SN is to conduct the observations at lower frequencies (e.g., 1.4 GHz). The radio emission at 1.4 GHz for events such as PTF 12gzk, SN 2007gr, and SN 2002ap is expected to peak after more than 10 days after explosion. Therefore, future surveys at low frequencies such as Apertif (Verheijen et al. 2008), and ASKAP (Johnston et al. 2008) have the potential to discover and follow many such SNe.

One of the main challenges in studying radio emitting SNe Ic at larger distances by either the VLA or future low-frequency surveys is ISS. As we probe further out, the angular size of the source decreases and therefore the effect of ISS increases. Nature, at this point, is becoming the main source of noise due to ISS. According to Figure 2, a SN-CSM shockwave, expanding at a velocity of  $0.3c$ , for example, will still exhibit more than 20% variability due to ISS at a distance of 50 Mpc, after 10 days. At the same time, one can take the approach of undertaking high-frequency (mm-wavelength) observations which are less susceptible to ISS modulation. Since high-frequency emission in PTF 12gzk-like events is expected to peak at  $\leq 1$  day after explosion, this approach will be effective only if immediate observations are initiated after the detection of a SN.

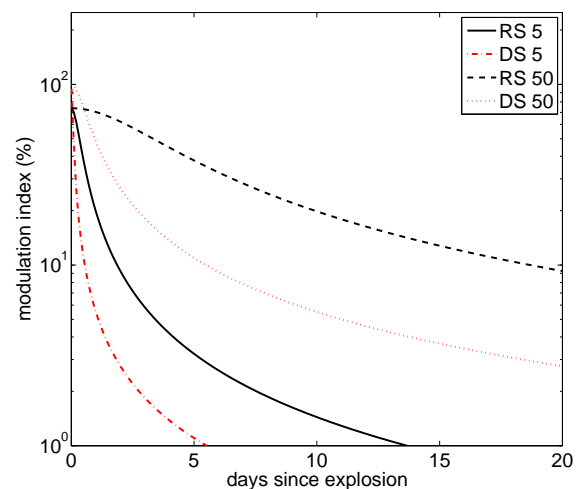


FIG. 2.— Modulation index for observations in the 5 GHz band of a supernova at a distance of 5 Mpc and 50 Mpc and expanding with a blast wave speed of  $10^5 \text{ km s}^{-1}$ . We assume  $\log(\text{SM}) = -3.63$ . The scattering strength is above unity and so both refractive broad-band scintillation (RS) and diffractive (narrow band) scintillations (DS) are seen. ISS calculations are based on Walker (1998).

To summarize, it is now clear that there exists a phase

<sup>14</sup> PTF 12gzk has narrow lines with a dispersion lower by a factor of  $\sim 4$  compared to broad-lined SNe Ic (see Ben-Ami et al. 2012b for details).

TABLE 2  
 $A_{\star}$  VALUES OF PTF 12GZK IN COMPARISON WITH OTHER SNe Ib/c

SN	Type	Velocity (optical) $\text{km s}^{-1}$	$A_{\star}$
1983N	Ib	18,200	1.15
1990B	Ic	17,700	2.0
1994I	Ic	17,500	2.8
2003L	Ic	12,000	34
2002ap	Ic-BL	38,000	0.04
2007gr	Ic	13,000	0.06
PTF 12gzk	Ic	35,000	$\leq 0.12$

Notes - The optical velocities are taken from Wheeler & Harkness (1990), Matheson et al. (2001), Millard et al. (1999), Matheson et al. (2003), Gal-Yam, Ofek, & Shemmer (2002), Hunter et al. (2009) and Ben-Ami et al. (2012), respectively. The  $A_{\star}$  values are from Chevalier & Fransson (2006) when equipartition is assumed and we adopt the value of  $\epsilon_B = 0.1$ .

space of fast SNe Ic that is still relatively unexplored. The improved capabilities of radio observatories combined with early discoveries by optical transient surveys will allow us to probe this new population of radio SNe. Such studies will provide a better understanding of the properties of the progenitor stars and their explosion energies, complementing previous work based on late-time observations.

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work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester. PTF is a fully-automated, wide-field survey aimed at a systematic exploration of explosions and variable phenomena in optical wavelengths. The participating institutions are Caltech, Columbia University, Weizmann Institute of Science, Lawrence Berkeley Laboratory, Oxford and University of California at Berkeley. The program is centered on a 12Kx8K, 7.8 square degree CCD array (CFH12K) re-engineered for the 1.2-m Oschin Telescope at the Palomar Observatory by Caltech Optical Observatories. Photometric follow-up is undertaken by the automated Palomar 1.5-m telescope. The research of A.G. is supported by grants from the ISF, BSF, GIF and Minerva, the EU/FP7 via an ERC grant, and the Kimmel award for innovative investigation.

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